VALIDATION OF AUTONOMOUS ROVER FUNCTIONALITY FOR PLANETARY ENVIRONMENTS

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ABSTRACT

This paper discusses autonomous rover functionality as it relates to planetary environmental issues and aspects of associated software validation. The focus is on Mars rover functionality and operational issues related to the Mars surface thermal environment, solar power usage, and terrain interactions with rover mobility systems. A hardware-centric approach to functional validation of Mars rover software is advocated. A brief example is discussed in the context of functional validation activities performed for the NASA Mars Exploration Rovers mission using a high-fidelity model of the *Spirit* and *Opportunity* rovers.

KEYWORDS: planetary rover, software validation, functional testing, Mars

1. INTRODUCTION

NASA employs autonomous rovers as surrogate explorers on remote planetary surfaces. The planetary environments impose significant constraints on the design and operability of robotic systems. Some of the current constraints are related or due to extreme temperatures, reliance on solar energy, and challenging terrain. For every mission, the rover software functionality required for mission success must be validated to ensure that it is adequate for enabling autonomous operation on planetary surfaces despite environmental effects on rover hardware. A variety of effective approaches exist for validating software using formal and informal methods depending on the application. Autonomous mobility software validation methods often include high-fidelity simulation and extensive physical testing as part of functional ("black-box") testing strategies for which a number of methods apply [1]. Despite the method(s) employed, engineers and project management must be convinced that autonomy software will satisfy related mission requirements at all levels.

Robotic vehicles for planetary surface missions are designed to effectively maneuver in a complex target environment and extend the reach of onboard science instruments beyond that of stationary landers. Whether the target environment is the planet surface or subsurface, mission success is in some way enabled by the mobility functionality. Recent and planned surface missions to Mars include requirements that rely on autonomous mobility to achieve mission success. As the need for autonomous mobility increases it is reflected more explicitly in mission requirements against which software must be validated.

The twin rovers landed on Mars in 2004 by the NASA Mars Exploration Rovers (MER) mission are explicitly required to use mobility in support of mission success. Software designs for these rovers include autonomous mobility functions of varying complexity for navigation on the Martian surface. General statements of the related autonomous mobility requirements are similar to the following: the rover(s) must be able to safely traverse some substantial minimum distance per day in terrain of some reference complexity while maintaining estimated position knowledge within some small percentage of distance traversed [2, 3]. The reference complexity of the terrain is typically as documented by images taken at landing sites of prior Mars missions. Requirements related to operability and survivability also apply. Generally, rovers must autonomously safeguard against environmental hazards during operation. Validation of required autonomous capabilities is not always straightforward since high-fidelity environment simulation is difficult to achieve, as is creation of all environmental conditions that might be encountered on planetary surfaces. The planetary environment constraints we focus on herein are thermal, power, and terrain related.

In Section 2, we discuss autonomous rover functionality as it relates to planetary environmental issues and aspects of associated software validation. A hardware-centric approach to functional validation of Mars rover software is advocated and described in Section 3. As an example, Section 4 provides a brief overview of related mobility validation activities involving a high-fidelity model of the MER *Spirit* and *Opportunity* rovers.

2. PLANETARY ENVIRONMENT EFFECTS

Modeling, simulating and/or predicting the functional behavior of rovers on natural terrain is not always practical. Climate and terrain conditions are often not precisely known or well understood prior to the rover's actual arrival at the landing site. Acquiring sufficient knowledge of the actual environment conditions requires extended operations on the surface in the region of the landing site. In this section, we discuss environmental effects and surface mobility characteristics that pose challenges for rover functional validation.

2.1 Thermal and Power Issues

Ground temperatures on Mars vary between wide extremes during each day-night cycle. For example, at the MER landing sites temperatures can vary up to 120° Celsius (C) each day, between -100° C at nighttime and 20° C during the daytime. In order to survive and execute its mission, the rover's critical electrical components (batteries, computer, etc) must not exceed extreme temperatures of -40° C to +40° C. In addition, certain components (e.g., motors) may only operate reliably within certain temperature ranges. In such extreme thermal environments internal temperature regulation is often necessary during rover operations. Perhaps the biggest unknown when addressing this problem is the Mars surface thermal environment at the landing site. It depends on several factors including landing site latitude, time of year, ground-absorbed solar radiation, thermal inertia (rock distribution), dust level in the atmosphere, and elevation [4]. Thermal regulation can be further complicated when all components do not share common operational temperature ranges. For example, batteries may require a temperatures to remain above -40° C at all times, while motors may require heating in order to operate when external temperatures are very low; when temperatures are optimal for motor usage they may be suboptimal for computer or instrument electronics, and so on. Rover designs typically address such concerns using software- and/or hardware-based temperature control systems. Related hardware may include temperature sensors, heaters, radiators, and thermostats as well as insulation materials.

Rovers that rely primarily on solar power employ solar arrays that can generate sufficient power for daily robotic activities. The amount of power that can be generated depends on the amount of solar energy absorbed by the solar array and therefore the conditions at the planet surface such as atmospheric opacity and terrain topography. For example, very dusty atmospheric conditions reduce the incident solar radiation and cause reduced rover power levels as long as the conditions persist. Prominent local terrain features that cast large areas of shadow have a similar effect. Even under the best conditions solar arrays can power the rover for a limited number of hours each day, thus limiting the time dedicated to daily exploration. While solar energy absorbed by a solar array is the primary power source for planetary rovers to date, some systems have the added luxury of an onboard battery that is rechargeable via the solar panel (although full-power capacity of the batteries degrade over time). Longer-term effects come into play as well and magnify the inter-relationship between power and thermal issues. For example, as the elevation of the sun changes over the course of a long mission, the available solar energy decreases. For the same reason, the rover experiences colder temperatures and requires additional power for thermal regulation. Meanwhile, power availability is being further reduced by long-term dust accumulation on the solar panels and degradations in battery capacity.

The implementation of homeostatic power and temperature regulatory mechanisms can be supported by onboard software in an intelligent manner. An operational readiness metric defined as a function of battery charge level and internal/external temperatures can be used as a basis for making intelligent decisions about homeostatic regulation. Decision rules can be formulated to classify the rover's operational readiness based on current states of temperature and available power. Low values of this metric would indicate unfavorable operating conditions and signal a need to execute temperature regulation and/or battery charging activities [5]. Such software would interface with low-level software for reading sensors and controlling regulation devices, and its behavior would be largely deterministic (as thermal and power models with quantified uncertainty are often available).

Verification of deterministic software behavior, or software that can be modeled reasonably well, can be addressed using formal methods [6]. The validation challenges increase considerably, however, as we move deeper into the autonomous functionality from software-software interactions to software-hardware interactions particularly due to transitions from determinism to non-determinism in software-induced system behavior. The non-deterministic system behavior manifests itself at the level of hardware-environment interactions, where the wheels interact with the terrain. At this level, it becomes more difficult to establish that the system is actually capable of executing the required mobility functionality.

2.2 Terrain Interactions

Successful mobility performance depends on complexity of the actual terrain and how well the rover is tested for that terrain. However, like surface thermal and solar energy issues, actual terrain topography and related characteristics are not often known until the rover is situated on the planetary surface. Reduced-gravity effects may further compound the complexities of interaction between mobility systems and unfamiliar planet surfaces. The result is non-deterministic behavior as wheels interact with terrain and increased uncertainty in how the autonomous mobility system will respond to motion commands.

Mobility and navigation problems for outdoor rough terrain vehicles are characterized by high levels of difficulty and increased measurement uncertainty. Complex motions outside of the ground plane occur quite frequently while traversing undulated terrain, encountering multidirectional impulsive and resistive forces throughout. In addition, common mobility and navigation sensor data inadequately represent the tremendous variability of surface features and properties of outdoor terrain. Such sources of uncertainty affect input interpretation and motion output execution, thereby reducing the predictability of system behavior.

Wheeled mobility systems are also subject to undesirable wheel-terrain interactions that cause wheels to slip on rocks and soil. Frequent loss of traction due to wheel slip during traverses from one place to another will detract significantly from the ability to maintain good rover position estimates. These factors impact the ability to guarantee required accuracy of localization estimates. In soft soils, loss of traction due to excessive wheel slippage can lead to wheel sinkage and ultimately vehicle entrapment. It is possible for wheels to sink to soil depths sufficient to prohibit rover progress over terrain, thus trapping the vehicle at one location. This is also possible on soils with insufficient bearing strength to support the rover. Such factors potentially impact our ability to guarantee compliance with traverse safety, distance, and/or localization requirements.

3. FUNCTIONAL SOFTWARE VALIDATION

The above discussion leads to the conclusion that it is non-trivial to realize regulation systems that optimally satisfy a superset of survival and operational ranges without over-constraining the overall operational regime for a rover system. Since homeostatic regulation of temperature and power can be achieved via software-software interactions that can be modeled and simulated, the use of formal methods for verification should suffice. The software could be verified and validated through operational testing using thermal environment chambers and solar energy simulators, or more simply using computer-generated inputs for temperatures and available power levels throughout their respective expected ranges. In this case, thermal and power regulation functionality can be readily evaluated using formal software verification methods such as model checking, which automatically search all realizable executions of an abstract model of the software for violations of requirements [6].

The above discussion also suggests that predictability of motion responses and mobility performance is hampered by non-deterministic wheel-terrain interactions that are difficult to model. How do we convince ourselves, then, that autonomous rover mobility software will perform well enough to execute mission functions as required? We respond to this challenge by conducting a validation/test program that aims to bind the relevant uncertainties to limits within which mobility requirements can be met with high probability. This requires extensive functional testing and system characterization. Thus, the approach is based on the notion that given sufficient testing, it is possible to make reasonably comfortable predictions about software capabilities [1]. Software-hardware interactions associated with mobility on natural terrain are most thoroughly evaluated by testing actual rover systems in realistic terrain.

3.1 Physical Testing

Effective mobility software validation methods generally rely upon the availability of one of more prototypes of a flight rover that is as similar as possible to the flight article (in physical configuration, subsystem functionality, etc). The higher the fidelity with respect to the flight article, the more value-added to the validation process by such prototypes. The model rover(s) can be tested in an arena such as an indoor sandbox collocated with the software development laboratory. Realistic outdoor facilities that resemble the planetary terrain as closely as is practical are also essential for focused field trials that validate terrain-dependent functionality, autonomous navigation algorithms, and operational readiness [7-9]. Small-scale indoor arenas are adequate for early incremental development and isolated testing of functionality and performance. However, the richer test environment offered by planetary analogue natural terrain is essential for characterization and exposure of software design problems that may not arise in small-scale settings.

The general validation approach for autonomous mobility software is hardware-focused and utilizes validation metrics such as requirements coverage, which ensure that all required functionalities are covered by at least one test [10].

3.2 Simulation-based Testing

Ideally, thorough evaluation of autonomous mobility software would consist of many navigation trials of physical rovers in physical terrain. However, this is not always the most practical approach. Computer simulations are useful as alternatives to maintenance of laborious test setups and they offer an automated means of achieving more complete coverage of software scenarios in lesser time than physical tests [11]. Simulated rover tests are also used to validate simulation predictions via comparison to actual physical tests.

Computer simulation is considered an attractive validation option in several situations: (1) in lieu of available rover hardware, (2) to improve test case coverage when there is insufficient time or resources for extensive hardware tests, (3) when there is a desire to avoid aggressive tests with critical rover hardware, and (4) when logistics of remote outdoor testing in analogue terrain are impractical. At present, however, we cannot model physical environment interactions associated with vehicle motion (i.e., wheel-terrain effects, soil mechanics, vehicle dynamics, etc.) well enough to rely on simulations alone for validating autonomous mobility software. A balance must be struck between functional hardware-based testing and high-fidelity simulation [12] that achieves the aim of the validation process.

In either case, test scenarios should be formulated and run under different terrain conditions to validate nominal and off-nominal functionality. Further validation should include robustness and characterization testing in environments of increased variability. Such testing permits refinement of the many tunable parameter values that are characteristic of autonomy software and govern its performance.

3.3. Example

A major portion of the MER mobility and navigation software functionality was tested, verified, and validated in facilities at JPL using several high-fidelity prototypes of *Spirit* and *Opportunity.* The main facilities used for this testing included an indoor sandbox arena and outdoor areas covered with loose gravel/sand and an assortment of rocks whose distribution could be configured as desired. A field test was also conducted in more natural terrain with varied features such as those expected at the MER landing sites. The field test was performed over a period of five days using one of the MER prototypes called the Surface System Test Bed (SSTB). The field venue for the test was a dry lakebed located in Edwards, California USA (almost 100 miles from JPL). At the field site, a small team of test engineers, rover engineers, and field geologists handled logistical activities while a small subset of the MER mission operations team (rover command sequence developers, rover mobility engineering analysts, and ground data system personnel) participated from JPL. Communications between field test computer workstations and mission operations ground data systems at JPL were achieved via satellite link. Objectives for the field test included testing traverse capability in natural terrain and exercising different scenarios in order to characterize system performance and tune relevant software parameters. Test scenarios were derived from mobility requirements for long distance traverses and short distance approaches to science targets.

The SSTB, shown in Fig. 1, is a fully functional prototype of the *Spirit* and *Opportunity* rovers used on Mars to conduct the MER mission. It falls short as an exact replica in that its solar panels are not populated with solar cells and its electronics are not complete or fully integrated with the vehicle. This rover model uses a tether that routes the necessary power and electrical signals to it from off-board power, communications, and ground data systems. The same tether routes commands and telemetry to and from the rover. Otherwise, this model is quite similar to *Spirit* and *Opportunity* in configuration, function, and capabilities.

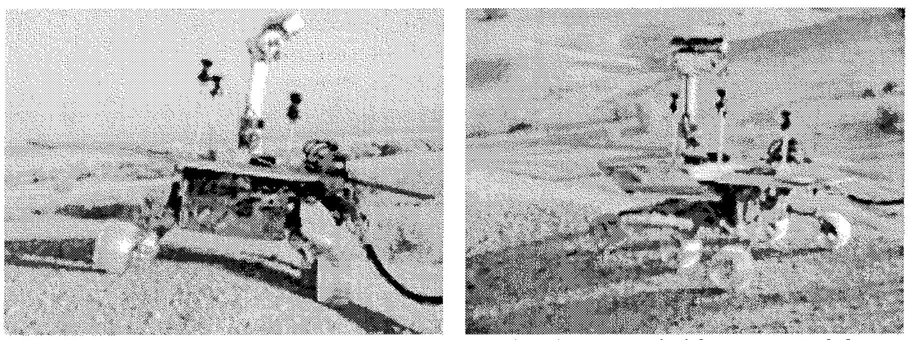

Figure 1. MER SSTB rover engineering model during a field test in California.

To build upon results of prior indoor and outdoor mobility validation tests at JPL, the SSTB rover was used effectively to validate navigation software functionality in more natural terrain. Navigation traverses were completed over shallow hills including short (~10 meters) approaches toward vertical walls, sloped walls, and discontinuous terrain drop-offs. These runs were valuable for acquiring stereo imagery of different types of terrain than were available in earlier test environments. Ground truth measurements of rover position and orientation throughout traverses were made using a Total Station surveying system (hence the reflecting prisms shown mounted on the rover in Fig. 1). The images acquired during traverses were also useful for off-line testing of image processing and hazard detection software at a later date, while the ground truth measurements enabled later analysis and assessment of performance relative to software requirements related to position accuracy.

5. SUMMARY AND CONCLUSION

Environmental phenomena that impact rover mobility and operations on planetary surfaces were discussed. Fundamental challenges presented by surface thermal environments, solar energy availability, and natural terrain interactions are described that complicate validation of software functionality. Validation approaches meant to meet the challenges are generally described. The suggested approach is focused on hardware-based functional testing to validate non-deterministic software-induced behavior, and suggests formal software verification methods for evaluating more deterministic functionality. As an example of the former, validation activities performed for the MER mission are briefly discussed.

Functional testing will not expose all potential problems with autonomous rover software since high-fidelity environment simulation is difficult to achieve. Moreover, the availability of sufficient resources (time, facilities, funds, personnel, etc), for exhaustive testing under all expected environmental conditions, is a rare luxury. Extensive testing in realistic settings enables performance characterization, which enables software tuning and predictability, as well as the ability to diagnose problems that arise during rover mission operations.

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